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(71) Applicant: SOVONICS SOLAR SYSTEMS  
6180 Cochran Road  
Solon Ohio 44139(US)

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(72) Inventor: Hanak, Joseph J.  
1028 Ridgedale  
Birmingham Michigan 48008(US)

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(74) Representative: Jackson, Peter Arthur et al,  
GILL JENNINGS & EVERY 53-64 Chancery Lane  
London WC2A 1HN(GB)

(54) Extremely lightweight, flexible semiconductor device arrays and method of making same.

(57) An extremely lightweight, interconnected array of semiconductor devices, such as solar cells, is formed from a large continuous area of semiconductor material (3, 23, 43, 83, 123) disposed on an unconventionally thin, electrically conducting substrate (1, 21, 41, 81, 121). The interconnections are formed by removing portions of the substrate to form substrate islands (13, 35, 55, 95, 141, 163, 183) underlying a layer of semiconductor material which underlies a transparent conductive oxide (5, 25, 45, 83, 125, 179). The oxide layer may likewise be formed into mutually isolated islands (7, 29, 47, 89, 131, 181) that overlay the areas between the substrate islands. Individual units or cells so formed may be interconnected by depositing a conducting material on, alongside and at least partially between islands of oxide and/or semiconductor, by depositing a metal grid (27) on the oxide layer and burning conducting paths (31) to the substrate islands, or by piercing the layers and disposing a conducting material in the holes (133) pierced.

The unconventionally thin substrate may be a sheet of electroformel nickel or other thin metal or may be an initially thick substrate that is thinned by chemical etching after other array processing steps are completed. To maximize the output power-to-weight ratio of a solar cell array, the conventional substrate (159, 171) may be removed entirely. In that process, a dissimilar layer (161, 173), such as a back reflector, is deposited on a support, such as a conventional substrate, before the semiconductor material (23, 177) is deposited. After all other processing, the support (159, 171) is removed by chemical etching to produce a substrateless array of devices. Typically, the array is encapsulated by a protective glass or polymer film. An encapsulant (33) is preferably applied to the exposed surface of the semiconductor material to protect it while the substrate is being thinned or removed. Subsequently, an encapsulant (37) is applied to the rear of substrate side of the array. An insulating layer (173) may be interposed between the support (171) and semiconductor layer (177) and act to encapsulate the rear of a substrateless array when the support is etched away to produce an ultimate power-to-weight ratio array.

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The unconventionally thin substrate may be a sheet of electroformel nickel or other thin metal or may be an initially thick substrate that is thinned by chemical etching after other array processing steps are completed. To maximize the output power-to-weight ratio of a solar cell array, the conventional substrate (159, 171) may be removed entirely. In that process, a dissimilar layer (161, 173), such as a back reflector, is deposited on a support, such as a conventional

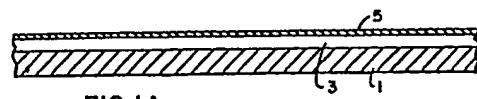


FIG. 1A

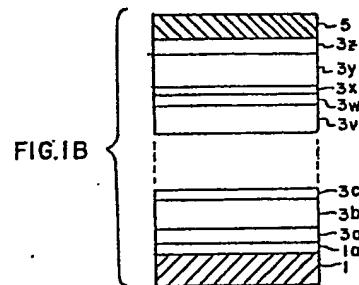


FIG. 1B

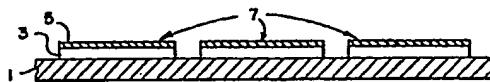


FIG. 1C

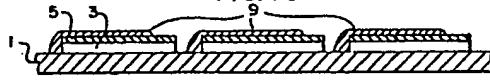


FIG. 1D

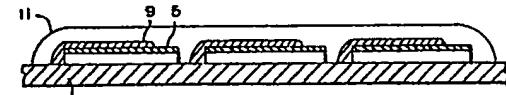


FIG. 1E

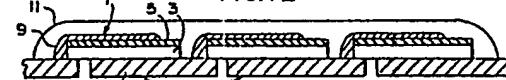


FIG. 1F

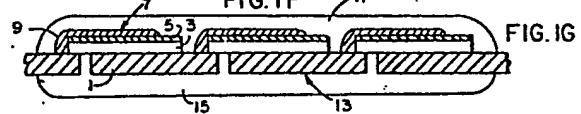


FIG. 1G

EXTREMELY LIGHTWEIGHT, FLEXIBLE SEMICONDUCTOR DEVICE  
ARRAYS AND METHOD OF MAKING SAME

This invention relates to arrays of interconnected semiconductor devices such as photovoltaic cells for direct conversion of sunlight into electrical energy. It is known that large area solar cell arrays can be produced on glass and relatively thick metal substrates. For example, such arrays may be produced by depositing an amorphous silicon alloy on coils of metal strips that may be unrolled for deposition and rolled again after the deposition. See United States Patents 4,410,558 for Continuous Amorphous Solar Cell Production System; 4,419,530 for Solar Cell and Method of Producing Same; 4,443,652 for 5 Electrically Interconnected Large Area Photovoltaic Cells and Method of Producing Said Cells; and 4,485,125 for Method of Continuously Producing Tandem Amorphous Photovoltaic Cells. It is also known that amorphous silicon can be deposited on thin foils of nickel prepared by an electroforming technique. See United States Patent 4,530,739 for 10 Electroplated Substrate. It has also been reported that amorphous silicon may be deposited by glow discharge on narrow plastic sheets 15 micrometers in thickness that are continuously drawn through a low pressure deposition chamber. See U.S. Patent No. 4,341,588.

Various methods of forming electrically interconnected arrays 20 of small-area photovoltaic cells from relatively large areas of deposited photoresponsive semiconducting materials are known. For example, in U.S. Patent 4,514,579, I have disclosed a "checkerboard" array of series-connected rows of photovoltaic cells in which the rows are electrically connected in parallel. Other series-connected arrays 25 are disclosed in U.S. Patent 4,245,386 to Kausche et al.

Traditionally, photovoltaic cells have been fabricated on a substrate that may be electrically conducting or may be an insulator. Typically, the substrate is the thickest member of a cell or an array of cells and contributes most of the weight to the cell or array. In

applications where weight is an important or critical factor, such as extraterrestrial or certain consumer uses, it is desirable to minimize the weight of a photovoltaic array, which means minimizing the weight of the substrate. A particularly lightweight, interconnected array of

5 devices could be made if the substrate were made unconventionally thin or a conventional substrate were eliminated entirely. However, use of a very thin substrate or no conventional substrate at all results in substantial difficulty in handling a large area of semiconductor material and forming it into an interconnected array.

10 In the invention, the problems of processing arrays of cells with an unconventionally thin substrate or without a conventional substrate are solved. Various alternative methods for producing such arrays have been developed. Arrays according to the invention are flexible and lightweight permitting them to be rolled for storage in a

15 relatively small volume. Because the weight of inventive photovoltaic arrays is small, the specific power, i.e. output power divided by weight, is very large and provides an apt factor for measuring performance. It is also possible according to the invention to maximize the specific power of a photovoltaic array by eliminating a conventional

20 substrate entirely.

The arrays formed according to the process are lightweight since they include only an unconventionally thin or no substrate, and preferably no more than a few hundred nanometers of semiconductor material. If, as is preferred, the semiconductor material is an

25 amorphous alloy, the structure is quite flexible and can be repeatedly rolled into a small diameter tube for storage and unrolled for use without damage.

Figures 1A through 1G are schematic cross-sectional end views, showing the steps in the fabrication of an interconnected array

30 according to one embodiment of the invention.

Figures 2A through 2F are schematic cross-sectional end views, showing the steps in the fabrication of an interconnected array according to one embodiment of the invention.

Figures 3A through 3G are schematic cross-sectional end views, showing the steps in the fabrication of an interconnected array according to one embodiment of the invention.

Figures 4A to 4H are schematic cross-sectional end views, 5 showing the steps in the fabrication of an interconnected array according to one embodiment of the invention.

Figures 5A to 5G are schematic cross-sectional end views, showing the steps in the fabrication of an interconnected array according to one embodiment of the invention.

10 Figure 6A is a top view and Figure 6B is a bottom view of an interconnected array according to one embodiment of the invention.

Figures 7A through 7G are schematic cross-sectional end views, showing the steps in the fabrication of an interconnected array according to one embodiment of the invention.

15 Figures 8A through 8G are schematic cross-sectional end views, showing the steps in the fabrication of an interconnected array according to one embodiment of the invention.

Figures 9A through 9E are schematic cross-sectional end views, showing the steps in the fabrication of an interconnected array 20 according to one embodiment of the invention.

In the invention a substrate is used for receiving a layer of semiconductor material. The substrate may be unconventionally thin or may be a conventionally thick substrate that is made unconventionally thin, preferably by chemical etching. In some embodiments, the 25 conventional substrate may be removed entirely, preferably by chemical etching leaving an unconventional, extraordinarily thin substrate. When the substrate is not completely removed, it is formed into islands for electrically interconnecting electronic devices, such as photovoltaic cells. When the substrate is completely removed, a conducting layer, 30 preferably optically reflecting, is formed into islands to act as an unconventional substrate for electrically interconnecting the devices that form the array. The semiconductor material may be formed into islands as part of the process of forming the devices and interconnecting them.

As used here, the term "island" means an isolated unit of the material that constitutes the island. That is, when a continuous sheet of semiconductor material or a substrate is formed into a plurality of islands, some of the semiconductor or substrate is removed completely, 5 in a direction generally perpendicular to length and width of the sheet, to expose the next subjacent, different kind of material. For example, forming islands of semiconductor material exposes substrate in the areas between those islands.

It is preferred, but not required, that the semiconductor be an 10 amorphous silicon or germanium alloy because those alloys can be readily deposited in very thin continuous layers or sheets covering large areas. Furthermore, those layers can be doped in a controlled way and single and multiple p-n and p-i-n structures can be created in them. It is also known how to deposit amorphous silicon structures on 15 electroformed nickel sheets that are no thicker than 10 micrometers. These techniques are disclosed in the United States patents described above. Thin layers of amorphous semiconductor alloys may be flexed without significant damage. All these properties aid in producing a lightweight, flexible array of devices according to the invention.

20 A continuous sheet of metal substrate and semiconductor material may be formed into an array of interconnected devices by numerous inventive methods as illustrated in the drawing figures. All of the figures are merely schematic and none are drawn to scale. In practice, the semiconductor material, conductive coatings, and back 25 reflectors are all tens and hundreds of nanometers thick, whereas the substrates are tens of thousands of nanometers thick. The drawing figures depict the formation of islands of various layers having sidewalls perpendicular to the next underlying layer. As those skilled in the art will appreciate, when the islands are formed by chemical 30 etching, the sidewalls develop a non-perpendicular slope with respect to the next underlying layer.

Turning to Figure 1, a series of six processing steps are illustrated by showing in cross-sectional view a structure including semiconductor material, preferably an amorphous silicon alloy containing defect compensating constituents, such as hydrogen and/or fluorine, to give performance equal to that of crystalline silicon. The structure, as shown in Figure 1A, includes an unconventionally thin electrically conducting substrate 1, preferably a metal such as stainless steel. In this example, the substrate is of an unconventional thickness such as less than 50 micrometers. The substrate may be an electroformed nickel sheet no thicker than 10 micrometers. A layer of semiconductor 3 is deposited on substrate 1. As shown in Figure 1B and as applicable to all processes and devices described here, semiconductor 3 may contain a series of layers 3a, 3b, ... 3y, 3z and substrate 1 may support a layer 1a intermediate the substrate and semiconductor. For example, layers 3a, 3b, etc. may be of differing conductivity types to form one or more n-p, p-n, p-i-n or n-i-p junction structures or p-p+ and n-n+ junctions might be used as ohmic contacts. The junctions are generally disposed in opposition to substrate 1. Intermediate layer 1a could be an electrically conducting or insulating material. When the devices to be prepared are photovoltaic cells, layer 1a is preferably an optically reflective material that enhances the performance of the cells and may include an underlying insulating material, as described in connection with two of the embodiments of the invention disclosed here.

As shown in Figure 1A, an electrically conductive coating 5 has been deposited on semiconductor 3 opposite substrate 1 to aid formation of electrical contacts. If the devices to be prepared according to the invention are to be photovoltaic devices, conductive coating 5 must be transparent to electromagnetic radiation, such as visible light, and may be a conductive oxide such as indium tin oxide, antimony tin oxide, or cadmium tin oxide.

In the illustrated procedure, the conductive coating and semiconductor are formed into a plurality of coextensive islands 7 by removing portions of the coating and semiconductor down to substrate 1. That is, in this example, the semiconductor in each island lies directly beneath and is of the same size as each island of conductive material. 5 The island formation may be accomplished by any known technique such as use of photosensitive masks followed by chemical etching or by scribing with a laser or water jet.

Next, as shown in Figure 1D, each island 7 is electrically 10 connected to substrate 1. In this example, a conductive material 9, preferably a highly conductive material such as a metal, is deposited on each island 7, along its side and at least partially between adjacent islands and in contact with the part of substrate 1 exposed between adjacent islands. Because of the relatively high lateral resistance of 15 thin layers 3 and 5, the electrical connection along the side wall of islands 7 does not adversely affect performance of the device being formed at each island. Conductive material 9 may be deposited by known methods such as screen printing a paste or condensing an evaporated metal on the structure, using conventional masking techniques. Although 20 conductive material 9 appears in Figures 1D through 1G to obscure most of the exposed surface of islands 7, material 9 is actually formed in fingers that are shown in cross section in the figures. As a result, the fingers obscure only a small fraction of the top surface of coating 5.

25 Then a protective insulative encapsulant 11 is applied to the side of the structure opposite substrate 1. The encapsulant may be a glassy material, such as silicon dioxide, silicon nitride, or silicon carbide, deposited by known techniques, or a polymer film. Such films include polyesters, polyurethanes, fluorocarbons, polyimides and 30 ethylene vinyl acetate (EVA) that may be thermally bonded or adhered to the structure to fill in all voids. It is useful to apply the encapsulant at this point in processing to provide maximum mechanical

strength to the flexible assembly for further processing steps. If the devices in the array are solar cells, then the encapsulant must transmit light as some glasses and the polymeric encapsulants do.

To complete the interconnection, islands 13 of substrate 1 are formed. In order to make the desired electrical connection between the cells, it is important that the areas between islands 13 underlie islands 7 of semiconductor material 3. The substrate islands are formed by conventional techniques such as masking and chemical etching.

As an inspection of Figure 1 shows, the individual devices are 10 electrically connected in series as a result of the processing just described. Although only an end view of the array is shown in Figure 1, it is understood that a plurality of series-connected strings of devices as shown may be connected in parallel to form a series-parallel array. In the case of photovoltaic cells, the series-parallel connections may 15 be chosen to produce a desired voltage and current output and are tolerant of many defects in individual cells as disclosed in my U.S.

Patent 4,514,579.

Finally, as shown in Figure 1G, an encapsulant 15 is applied to the substrate side of the assembly. The encapsulant may be a glassy 20 material or a polymer like EVA, but need not be transparent. Obviously, it is necessary to apply an electrical connection to each of the two substrate islands at opposite ends of the series-connected string to prepare a useable array. These contacts may be applied by conventional means.

25 Another method of forming an interconnected array is shown in Figure 2 in six parts, 2A through 2F. The same starting material is used as in Fig. 1A. In Figure 2A, an unconventionally thin conducting substrate 21 bears a semiconductor material 23 that may be an amorphous silicon alloy containing a number of junctions opposite substrate 21. A 30 conductive coating 25, which may be a transparent oxide, is deposited on semiconductor 23 as shown in Figure 2B. A metal grid having a plurality of fingers 27 is deposited on coating 25, for example, by condensing a metal from a vapor and using conventional masks and etchants as necessary to establish the desired finger dimensions.

Islands 29 of coating 25 are formed beneath grid 27. As is preferred (but not shown in Figure 2), islands 29 project beyond the width of fingers 27. Each grid finger 27 is electrically connected to substrate 21 through coating 25 and semiconductor 23. The electrical connection is formed by "burning" a highly conducting path 31 from each finger 27 through coating 25 and semiconductor 23 to substrate 21. Paths 31 may be created by briefly passing a relatively large localized current through the path, much in the nature of spot welding. Alternatively, a high energy density laser beam may be directed at each finger 27 to form each of the highly conducting paths 31 that are shown schematically in Figure 2D.

As already described in relation to Figure 1, an encapsulant 33 is applied to the front surface of the structure opposite substrate 21. See Figure 2E. Thereafter, islands 35 of substrate 21 are formed with the areas between islands 35 being disposed beneath islands 29 rather than being aligned with islands 29. Islands 35 may be formed by conventional masking and etching techniques. Finally, as with the structure of Figure 1, a rear encapsulant 37 is applied to the substrate side of the structure. Electrical contacts are applied to two substrate 20 islands 35 at the extreme ends of the series-connected devices before the encapsulation.

Although the methods just described produce lightweight, flexible interconnected arrays of devices, sometimes wrinkling of the first applied encapsulant occurs while the substrate is being processed. By making some changes in the order of the process steps, encapsulant wrinkling can be avoided. Two such processes according to the invention are illustrated in Figures 3 and 4.

Referring to Figure 3, there is the same beginning structure as before. An unconventionally thin, conducting substrate 41 has deposited on it a layer of semiconductor 43, preferably an amorphous silicon alloy that may include one or more differing conductivity type junctions. An electrically conductive coating 45 deposited on semiconductor 43 may be

a transparent conductive oxide. The structure is then processed, for example, by laser scribing, water jet scribing or conventional masking and etching, to form islands 47, each comprising coextensive islands of semiconductor material 43 and overlying conductive coating 45. In order

5. to perform as many processing steps as possible before encapsulation, the position of islands of substrate 41 are next established by depositing a mask 49 on the substrate as shown in Figure 3C. The mask is applied in a conventional way, for example, using well known photoresist masks, to establish the pattern for the substrate islands.

10 As shown in Figure 3C, mask 49 defines the substrate islands so that the spaces between them will be disposed beneath islands 47.

In Figure 3D a step of depositing a metal 51 in electrical contact with substrate 41 between islands 47 and on top of each of islands 47 is shown. This is the same step described for Figure 1D and

15 may likewise be completed by condensing a metal vapor or by screen printing. Then an encapsulant 53, such as a glassy material or a polymer, is applied to the side of the structure bearing islands 47 as described in connection with Figures 1E and 1G. A polymer encapsulant may be applied with heat or an adhesive.

20 Islands 55 of substrate 41 are formed by chemically etching the substrate. By applying mask 49 before encapsulation, encapsulant 53 is not subjected to the heat used to cure the mask and therefore does not wrinkle. Avoidance of wrinkling is important to produce a planar array and to obtain accurate mask registration. Mask 49 may also be left in

25 place after etching to avoid exposure of encapsulant 53 to the solvent used to remove the mask. Electrical contacts 57 and 59 are applied to islands 55 at the extreme ends of the string, through mask 49, if necessary.

Finally, a glassy or polymer encapsulant 61 is applied over the

30 substrate side of the structure, much like encapsulant 53. As indicated in Figure 3E, encapsulant 53 may consist of two parts. A potting compound may be applied to the semiconductor side of the structure

before a sheet encapsulant is applied. The potting compound will flow into the areas between islands 47 and eliminate voids. Since voids are potentially present between substrate islands 55 also, it may also be desirable to apply a potting compound to the substrate side of the structure before encapsulant 61 is applied.

5 A different embodiment of the invention in which the encapsulants are not exposed to thermal curing, or solvents related to masking, is illustrated in Figure 4. There, the starting material shown in Figure 4A is the same as in earlier examples, except that the 10 conducting coating has not yet been applied.

A substrate 81 has deposited on it a semiconductor material 83, that may be an amorphous silicon alloy and may contain one or more electrical junctions disposed opposite substrate 81. Semiconductor 83 is divided into islands 85 by scribing with a laser or water jet or by 15 conventional masking and etching techniques. Then an electrically conducting coating 87 is deposited over and between semiconductor islands 85 so as to be in electrical and mechanical contact with islands 85 and substrate 81 in the areas between islands 85. In this way the top surface of each of islands 85 is electrically connected to substrate 20 81. However, islands 85 are not short circuited because of the high lateral resistance of thin semiconductor layer 83. Coating 87 may be a transparent conductive oxide such as indium tin oxide or one of the other oxides already identified herein.

As shown schematically in Figure 4D, coating 87 is formed into 25 islands 89 by removing some of the coating material 87 lying directly over each of islands 85. Thereafter, a mask 91 is applied to substrate 81 for later use in forming substrate islands and the mask is cured as necessary. Conventional photoresist materials may be used as mask 91. As shown in Figure 4E, the openings in mask 91 are aligned beneath 30 islands 85 to produce, ultimately, a series electrical connection between at least some of the devices in the array being formed.

Upon completion of the masking step, an encapsulant 93 is applied to the conductive coating side of the structure. Encapsulant 93 may include a potting compound applied directly to the structure followed by a protective glassy or polymer film, or the glassy or 5 polymer film may be applied directly to the structure.

Thereafter, substrate 81 is etched through mask 91 to form islands 95 of substrate 81. Because the spaces between islands 95 lie below semiconductor islands 85 and the spaces between conductor islands 89 lie above semiconductor islands 85, the devices are connected in 10 series. Electrical contacts 97 and 99 are attached to substrate islands 95 at the extreme ends of the string. Finally, an encapsulant 101 is applied to substrate 81. Again, mask 91 may be left in place to avoid exposing an encapsulant to any solvents, so long as electrical contacts 97 and 99 penetrate the mask to reach substrate 81. Encapsulant 101 may 15 be a glassy material or polymer and may include a potting compound in direct contact with substrate 81.

Still other embodiments of the invention exist. It is desirable in some cases to avoid etching the semiconductor layer since that process requires use of corrosive liquids or semi-liquids that may 20 attack a metal substrate. A process according to the invention that avoids etching of the semiconductor is depicted in Figure 5.

In Figure 5A the usual starting material of an electrically conducting, preferably metal, unconventionally thin substrate 121 is shown bearing a semiconductor layer 123. As before, semiconductor 123 25 may be an amorphous silicon alloy and may contain one or more junctions disposed opposite substrate 121. An electrically conductive coating 125 is disposed on semiconductor 123 and may be a transparent conductive material such as indium tin oxide. As seen in Figure 5B, masks are next applied to both sides of the structure. These may be conventional 30 photoresist material masks. The mask on coating 125 is patterned to define islands 127. The mask on substrate 121 defines another set of islands 129. Again, the spaces between substrate mask islands 129 are disposed beneath mask islands 127 in order that the desired series electrical connection be produced in the final product.

Transparent coating 125 is then etched through mask islands 127 with a mild etch. For example, a hydrogen iodide solution may be used to remove indium tin oxide and form coating islands 131. A channel 133 is formed adjacent each coating island 131 passing through semiconductor 5 123, substrate 121 and mask island 129. Channels 133 may be punched with a sharp instrument like a needle because of the thinness of the layers. Typically the total thickness of coating and semiconductor layer does not exceed a few hundred nanometers and the substrate typically is less than about 100 micrometers in thickness.

10 Channels 133 are filled with a conductive material such as a silver paste by a suitable method such as screen printing. The paste is forced into channels 133 and patterned so as to contact the top and side of coating islands 131 and to extend out of substrate mask islands 129 to form a raised contact point 137 at the substrate side of the 15 structure.

An encapsulant 139, which may include a potting compound in direct contact with islands 131, is applied to the semiconductor side of the structure. Encapsulant 139 may be a glass or polymer film and must be transparent to light if the interconnected semiconductor device array 20 comprises photovoltaic cells. With one side of the structure protected by an encapsulant, substrate 121 is etched away between mask islands 129 to form substrate islands 141 and complete the series electrical connection of the array. Electrical contacts 143 and 145 are attached to the extreme opposite substrate islands 129. Finally, the substrate 25 side of the structure has an encapsulant 147 applied to it in the manner and composed of the various alternative constituents already mentioned.

Plan views of a structure that may result from the method just described in relation to Figure 5 are shown in Figure 6. In Figure 6A, a top view is shown; in Figure 6B, a view from the bottom of the array 30 is shown. As is clear to the skilled person from the figures, two series-connected strings of three devices each are shown. The two series-connected strings are electrically connected in parallel. The

parallel connection is achieved by eliminating any mutual electrical isolation of the substrate islands at the ends of each series-connected string. Electrical contacts 135 are as shown in cross-section in Figure 5, but because of their relatively long depths, the contacts each have 5 three fingers 149 extending over each island 131 of conductive material 125, as shown in Figure 6. This multiple finger contact configuration allows increased current flow without increased electrical resistance. For the same reason, each contact includes not one, but three channels 133 containing an electrically conductive material such as a silver 10 paste. Obviously, the module of Figure 6 can be expanded. If the devices are photovoltaic cells, expansions by adding cells in a direction parallel to fingers 149 would result in increased voltage output and addition of cells in the transverse direction would result in increased current flow.

15 I have been successful in preparing a number of embodiments of the invention having amorphous silicon photovoltaic cells interconnected in an array. A square array .3 meters on a side having an active area of about .075 square meters was prepared according to the methods depicted in Figures 3 and 4. The array included ten parallel-connected 20 strings of p-i-n cells. Each string included twelve series-connected cells. The array produced 1.6 watts of power under AM1 illumination (equivalent to an overhead sun with the terrestrial atmosphere interposed between the sun and the array) with an open circuit voltage of 7 volts, a short circuit current of 640mA and a fill factor of 0.35.

25 An array produced by the method depicted in Figure 5 had the same 10 by 12 cell structure and size. A polyester encapsulant about 40 micrometers thick was applied to both sides of the array with a roller. The array weighed 14 grams and produced 300 milliwatts of power under AM1 illumination for a specific power of 21 watts per kilogram. By 30 continuously optimizing the handling techniques just described, I have produced embodiments of the invention according to the methods described above having specific powers as high as 110 watts per kilogram. For storage, the arrays described can be rolled into a tube as small as about 38 millimeters in diameter without damage.

In the embodiments of the invention just described the starting material has included a continuous semiconductor layer deposited on a continuous, unconventionally thin electrically conducting sheet. The term "continuous," as used here, means that the semiconductor and 5 substrates extend over a large area without interruption. The substrates are ordinarily very thin to produce a flexible lightweight array. That is, they are on the order of 125 micrometers thick and may be as thin as 10 micrometers or less when electroformed nickel substrates are used. Such thin foils are difficult, but not impossible, to handle in 10 continuous deposition apparatus such as is described in the patents referenced above. For those machines it is easier to handle continuous substrates on the order of 250 micrometers in thickness. However, such a thick substrate substantially reduces the specific power of a photovoltaic array.

15 The thick substrate problem can be solved in a number of ways. A substrate of conventional thickness may be used and processed by one of the methods previously described, but with the following modification. Before masking, etching or encapsulating the substrate side of the structure, but preferably after encapsulating the 20 semiconductor side of the structure, the substrate thickness may be reduced to the preferred, unconventional thickness by etching. An example of such a process is shown schematically in Figure 7 using the steps and reference numbers of Figure 2. The same technique is applicable to the processing methods shown in Figures 1 and 3-5. In the 25 processing steps of Figure 7, substrate 151 is of conventional thickness through the step of Figure 7E and all processing steps are the same as those already described for Figure 2, so there is no need to repeat the description. In the step depicted as Figure 7F, the substrate is reduced in thickness by chemical etching. Stainless steel substrates 30 may be etched by conventional means with a ferric chloride solution to reduce them to the desired thinness.

I have succeeded in reducing the thickness of a stainless steel substrate from 200 micrometers to 38 micrometers in this way. The resulting structure, which had a 38 micrometer polyester lamination, was quite flexible. Arrays producing specific powers of 60 watts per 5 kilogram can readily be achieved in this manner. In another case, I have successfully reduced a 200 micrometer thick stainless steel substrate to a thickness of 20 micrometers. That array, having an active area of about .074 square meters, and ten parallel-connected strings of twelve series-connected cells each, each cell composed of two 10 series-connected p-i-n devices, produced an open circuit voltage of 18.5 volts and a short circuit current of 260 mA, with a fill factor of 0.46.

In all of the examples just described, the major source of weight is the substrate even though it is unconventionally thin. That weight ultimately limits the specific power output of the array. 15 Therefore, maximizing the specific power of an array according to the invention requires complete removal of the conventional substrate. Some supporting structure is necessary, however, and it is important that the semiconductor layer be protected from the etchant used during the substrate removal. That protection can be provided by first depositing 20 on a support substrate an intermediate layer having a chemical composition that does not react with a support substrate etchant. After other processing, the support substrate is etched away without damage to the intermediate layer. It is known that a reflective surface disposed at the deepest portion of a photovoltaic cell enhances performance by 25 reflecting unabsorbed radiation back through the cell. Thus, if the array consists of photovoltaic cells, the intermediate layer is preferably optically reflective. Such reflecting, protective layers may be formed, for example, of titanium or of a silver-titanium alloy.

A process according to this aspect of the invention is depicted 30 in Figure 8 using the processing steps and reference numbers of Figure 2. The same technique may be applied to the processing methods shown in Figures 1 and 3-5. In Figure 8A, the starting material includes a

support 159 upon which an etch-resistant reflecting layer 161, such as a titanium alloy, has been deposited. Support 159 may be of conventional substrate thickness or may be unconventionally thin. Reflecting layer 161 is typically a few hundred nanometers in thickness. All the 5 processing steps of Figures 8A through 8E are similar to those of Figure 2 though Figure 2E, therefore there is no need to repeat their description. In Figure 8F support substrate 159 is entirely etched away leaving layer 161 as the rear contact and back reflector of the photovoltaic cell. Reflecting layer 161 is divided into islands 163 10 having their spaces disposed beneath the islands of conductive coating. Electrical contacts (not shown) and encapsulant 37 are applied to reflecting layer 161 as already described with respect to Figure 2. The result is a very flexible array of interconnected devices with an outstanding specific power, since the mass of a conventional substrate 15 is entirely removed. Reflective layer 161 acts as an unconventional substrate since it is, typically one half of a micrometer in thickness or less.

Still another example of a method of producing an array according to the invention producing an ultimate specific power is 20 illustrated in Figure 9. The starting structure shown in Figure 9A includes a support 171, which may be a conventional metallic substrate, upon which a relatively thin insulating layer 173, such as a polyimide approximately 10 micrometers in thickness, has been deposited. A relatively thin, optically reflective layer 175 has been deposited on 25 polyimide 173. Layer 175 may be an aluminum, five percent silicon alloy approximately 250 nanometers in thickness covered with a very thin layer of chromium. The chromium layer may be about 3 nanometers thick. The surface of this particular example of an optically reflective layer is not specular, but rather has a textured appearance that functions well 30 in photovoltaic cells to improve efficiency by reflecting light. The reflective layers may be deposited by conventional means such as by magnetron sputtering at temperatures of about 250 to 300°C.

A semiconductor layer 177, preferably an amorphous silicon alloy, is deposited on reflective layer 175, for example by the continuous glow discharge processes described in the patents identified at the beginning of this description. A conductive coating 179, which 5 is transparent if the array comprises photovoltaic cells, is deposited on semiconductor 177. Coating 179 may be a transparent oxide such as indium tin oxide.

The structure of Figure 9A is then masked and etched in a conventional manner to form coextensive islands 181 of semiconductor 177 10 and coating 179 as shown in Figure 9B. Alternatively, islands 181 may be formed by water jet or laser scribing. In this embodiment, there is no access to reflective layer 175 from the support side of the structure because of the presence of insulator 173. Therefore, islands of the reflective layer 175 for making the electrical contacts must be prepared 15 from the semiconductor side of the structure. As shown in Figure 9C, islands 183 of reflective layer 175 are formed by known means, such as masking and etching. In the specific example described, the chromium layer is so thin that is readily penetrated by an etch that attacks the aluminum silicon alloy. A portion of each island 183 is coextensive 20 with one of islands 181. An additional portion of each of islands 183 extends from beneath one side of each of islands 181 for making electrical connections. An insulator 185 is then applied to the side of islands 181 from which islands 183 do not extend. Insulator 185 may be a transparent lacquer or other liquid or paste that is screen printed to 25 form a solid, tough insulator. The insulator avoids the short circuiting of cells that would result if any of islands 183 were electrically connected together when the series electrical connections are made. An electrically conducting material 187, such as a silver paste, is screen printed on the top of each island 181 and over 30 insulator 185, to contact the portion of island 183 projecting from the next adjacent island. The contacts thus formed are shown in Figure 9D electrically connecting the individual cells in series. Finally, to achieve the goal of ultimate specific power, support 171 is entirely removed by etching as indicated in Figure 9E.

Before support 171 is etched away, the surface of the structure bearing contacts 187 may be encapsulated with a polymer or glassy, preferably transparent, layer that may be preceded by a pottant (neither of which are shown). Electrical contacts are applied at the ends of the 5 series-connected string before laminating the surface bearing contacts 187. Insulator 173 forms a rear encapsulation for the structure without further processing.

For some applications, such as outer space, it is undesirable to use a polymeric front encapsulant because it is attacked by ions. A 10 glassy transparent encapsulant, such as silicon dioxide, silicon nitride or silicon carbide, is required in this application and may be deposited on the array by known chemical vapor deposition or plasma deposition techniques.

Using this ultimate, lightweight array technique just 15 described, I have prepared an array of amorphous silicon alloy photovoltaic cells weighing 67 grams per square meter and generating 33 watts per square meter for a specific power of 492 watts per kilogram.

CLAIMS

1. A process for producing a flexible, lightweight electrically interconnected array of semiconductor devices from a continuous sheet of semiconductor material disposed on an electrically conducting substrate, said process comprising:

5 disposing a semiconductor material (3, 23, 43, 83, 123) on an electrically conducting, flexible substrate (1, 21, 41, 81, 121, 151);  
disposing an electrically conducting, transparent coating (5, 25, 45, 87, 125) on said semiconductor material;  
selectively removing portions of said coating to form a 10 plurality of islands (7, 27, 47, 89, 131) of said coating; and  
electrically connecting each of at least two adjacent islands of said coating to said substrate; characterized by  
selectively removing a portion of said substrate underlying each of said at least two adjacent islands of said coating to form a 15 plurality of islands (13, 35, 55, 95, 141) of said substrate and to connect said at least two adjacent islands of said coating in series electrically through said semiconductor material and said islands of said substrate.

2. The process of claim 1 characterized in that said 20 substrate (1, 21, 41, 81, 121, 151) is less than 50 micrometers in thickness.

3. The process of claim 2 characterized in that said substrate (1, 21, 41, 81, 121, 151) comprises electroformed nickel no more than 25 micrometers in thickness.

25 4. The process of claim 1 characterized by, before said removing portions of said substrate step, applying a continuous encapsulant (33) over said islands (27) of said coating (25) and areas therebetween and reducing the thickness of said substrate (151) to less than 25 micrometers.

5. The process of claim 1 characterized by, before said electrically connecting step, selectively removing portions of said semiconductor material (43) to form an island (47) of semiconductor material underlying each of said at least two adjacent islands (47) of said coating and said step of electrically connecting each of said at least two islands of said coating to said substrate comprises depositing an electrically conducting material (51) on, and alongside, each of said at least two islands of said coating and semiconductor material and in electrical contact with said substrate.

10 6. The process of claim 1 characterized by, before said removing portions of said coating step, depositing a metal grid on said coating, said grid having a plurality of fingers (27), said selectively removing portions of said coating step including leaving an island (29) of said coating (25) underlying each of said fingers, and said 15 electrically connecting step comprises establishing an electrically conducting path (31) from each of at least two of said fingers to said underlying substrate (21, 151) through said at least two islands of said coating and through said semiconductor material (23).

7. The process of claim 1 characterized by, before said 20 disposing a coating step, selectively removing portions of said semiconductor material to form a plurality of islands (85) of said semiconductor material (83) and said disposing a coating step includes disposing said coating (87) on said islands of said semiconductor material and on said substrate (81) between said islands of said 25 semiconductor material.

8. The process of claim 7 characterized in that said selectively removing portions of said coating and said electrically connecting steps include removing a portion of said coating overlying each of said at least two islands of said semiconductor material and 30 said selectively removing portions of said substrate step comprises removing a portion of said substrate (81) underlying each of said at least two islands of said semiconductor material.

9. The process of claim 1 characterized by, after said selectively removing portions of said coating step, piercing, adjacent each of said at least two adjacent islands (127) of said coating, a channel (133) passing through said semiconductor material (123) and said 5 substrate (121) and said electrically connecting step comprises applying a conductive paste (135) on, and at least partially between, said at least two islands of said coating, through said channels, and in contact with said substrate.

10. A process for producing a flexible, lightweight 10 electrically interconnected array of semiconductor devices from a continuous sheet of semiconductor material disposed on a substrate, said process comprising:

disposing a flexible, electrically conducting layer (161, 175) on a substrate (159, 171) formed of a material different from that of 15 said layer;

disposing a semiconductor material (23, 177) on said layer; and disposing an electrically conducting, transparent coating (25,

179) on said semiconductor material; characterized by

selectively removing portions of said coating to form a 20 plurality of islands (29, 181) of said coating; and

electrically connecting each of said at least two adjacent islands of said coating to said layer; and

removing said substrate.

11. The process of claim 10 characterized in that said 25 electrically conducting layer (161, 175) is less than .5 micrometers thick.

12. The process of claim 10 characterized by, after said removing said substrate step, selectively removing a portion of said layer (161) underlying each of said at least two adjacent islands (29) 30 of said coating (25) to form a plurality of islands (163) of said layer and to connect said at least two adjacent islands of said coating in series electrically through said semiconductor material (23) and said islands of said layer.

13. The process of claim 10 characterized by, before said electrically connecting step, selectively removing portions of said semiconductor material to form an island of semiconducting material underlying each of said at least two adjacent islands of said coating and said step of electrically connecting each of said at least two adjacent islands of said coating to said layer comprises depositing an electrically conducting material on, and alongside, each of said at least two adjacent islands of said coating and semiconductor material and in electrical contact with said layer.

10 14. The process of claim 10 characterized by, before said disposing a coating step, selectively removing portions of said semiconductor material to form a plurality of islands of said semiconductor material and said disposing a coating step includes disposing said coating on said islands of said semiconductor material and on said layer between said islands of said semiconductor material.

15 15. The process of claim 14 characterized in that said selectively removing portions of said coating and said electrically connecting steps include removing a portion of said coating overlying each of at least two adjacent islands of said semiconductor material and said selectively removing portions of said layer step comprises removing a portion of said layer underlying each of said at least two adjacent islands of said semiconductor material.

20 16. The process of claim 10 characterized in that said substrate comprises a relatively thick support layer (171) having a relatively thin insulating layer (173) disposed thereon, said electrically conducting layer (175) being disposed on said insulating layer and said removing said substrate step comprises removing said support layer.

25 17. The process of claim 16 characterized by, before said electrically connecting step, selectively removing portions of said semiconductor material (171) to form a plurality of islands of said semiconductor material (181), one of said islands of semiconductor

material underlying each of said at least two adjacent islands of said coating (179), and selectively removing portions of said electrically conducting layer (175) to form a plurality of islands (183) of said conducting layer, one of said islands of conductive layer underlying and

5 laterally projecting from each of said islands of semiconducting material underlying said at least two adjacent islands of said coating.

18. The process of claim 17 characterized in that said electrically connecting step comprises depositing an insulator (185) along a side of each of said at least two adjacent islands of coating (181) to insulate said islands (183) of said conducting layer (175) between said islands of said coating from each other and depositing an electrically conducting material (187) on and in electrical contact, respectively, with each of said at least two adjacent islands of coating, and on and in electrical contact with said respective laterally

10 projecting islands of said layer.

15

19. A flexible, lightweight array of interconnected semiconductor devices comprising:

an electrically conducting, flexible substrate (175);

a layer of semiconductor material (177) deposited on said

20 substrate; and

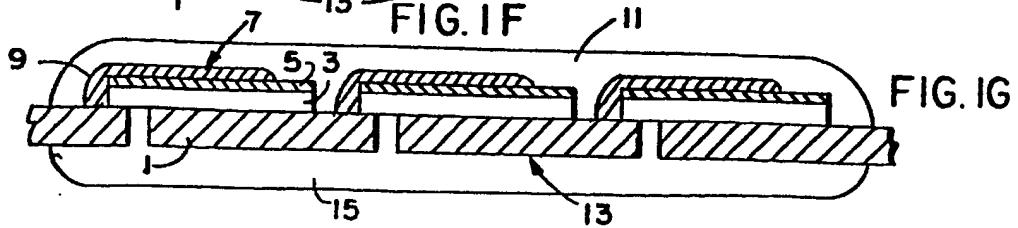
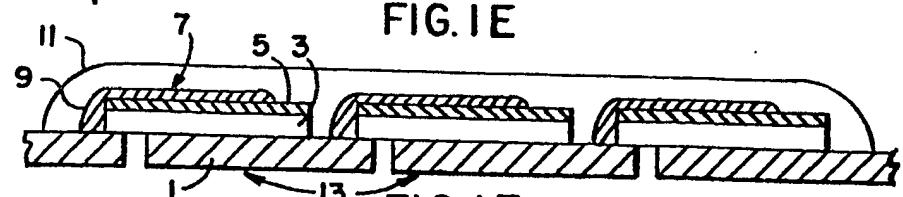
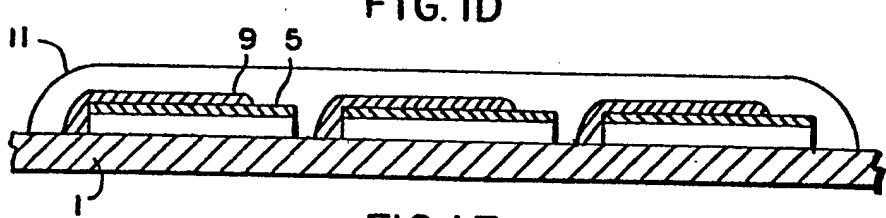
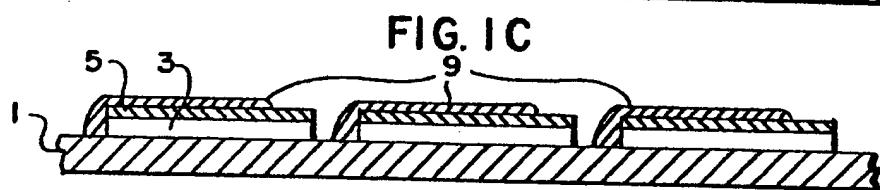
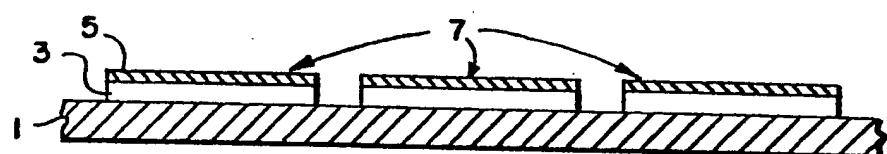
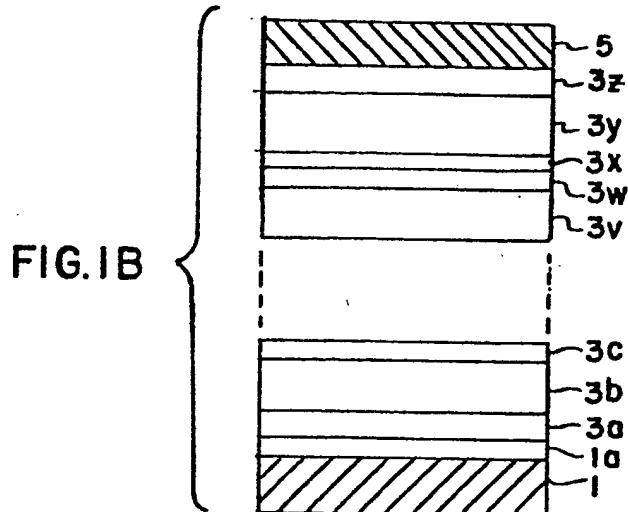
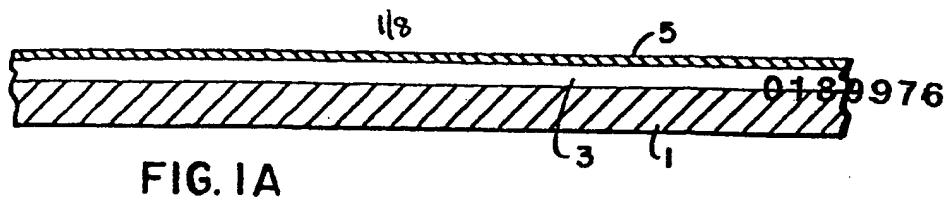
an electrically conducting, transparent coating (179) deposited on said semiconductor, wherein said coating and semiconductor material are formed into a plurality of substantially coextensive islands (181) and spaces therebetween and at least two adjacent islands of said

25 coating are electrically connected in series through said semiconductor material, and said substrate is divided into a plurality of islands and areas therebetween, said areas between said substrate islands not underlying either of said at least two adjacent islands of said coating, said islands of substrate laterally projecting from beneath said at

30 least two adjacent islands of said coating; characterized in that

an insulator (185) is disposed on a side of each of said at least two adjacent islands of said coating in contact with said substrate island underlying said respective island of said coating, and each of said at least two adjacent islands of said coating is connected to a different one of two of said islands of said substrate by an electrically conducting material (187) disposed on each of said at least two adjacent islands of said coating, on said insulator and extending to one of two of said laterally projecting islands of said substrate.

5. 20. The array of claim 19 characterized in that said substrate 10 (175) is less than 0.5 micrometers thick.



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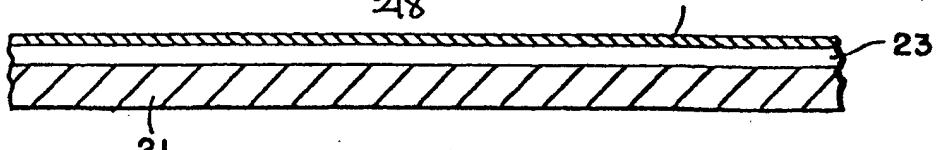


FIG. 2A

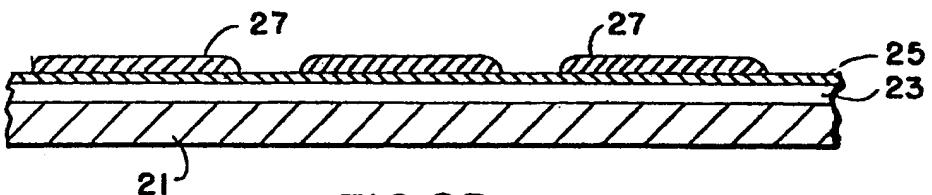


FIG. 2B

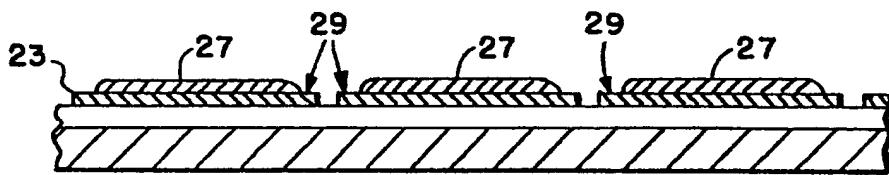


FIG. 2C

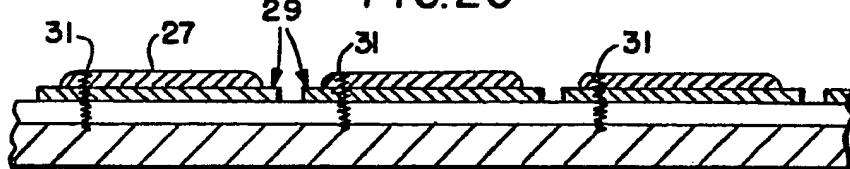


FIG. 2D

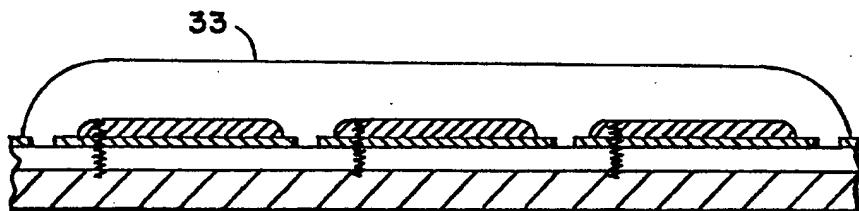


FIG. 2E

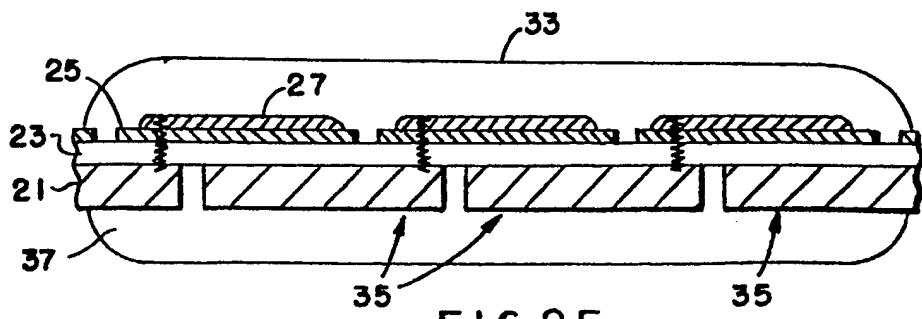


FIG. 2F

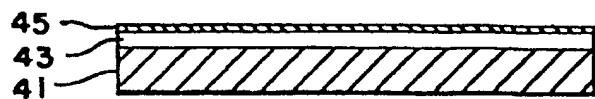


FIG. 3A

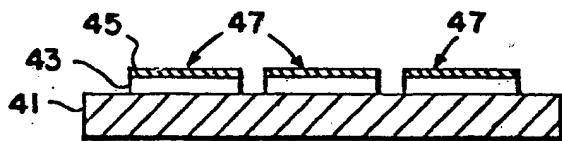


FIG. 3B

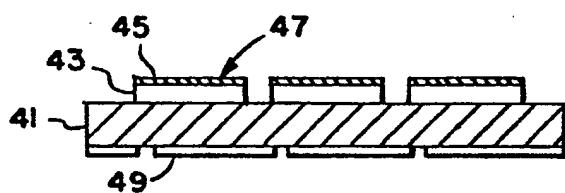


FIG. 3C

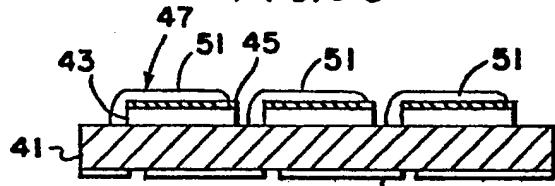


FIG. 3D

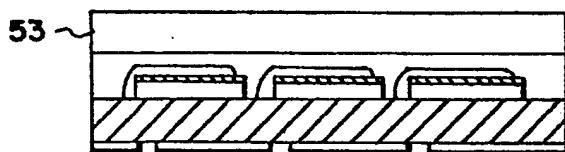


FIG. 3E

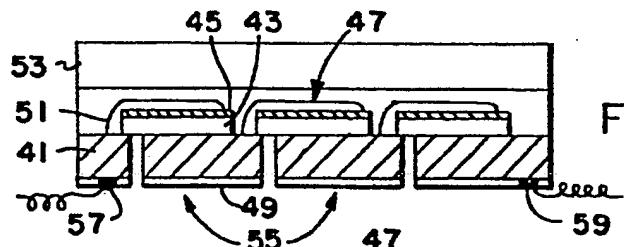


FIG. 3F

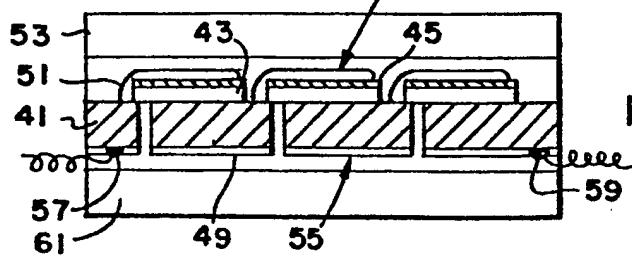
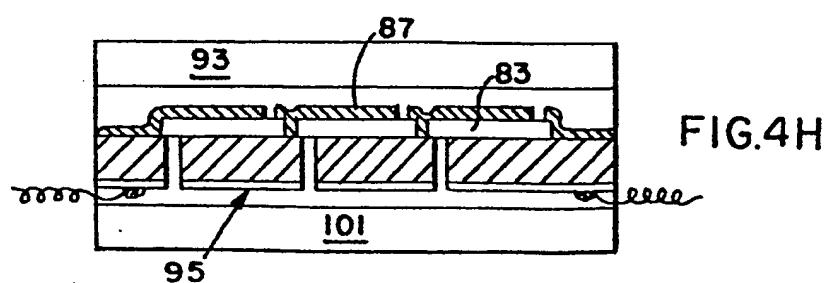
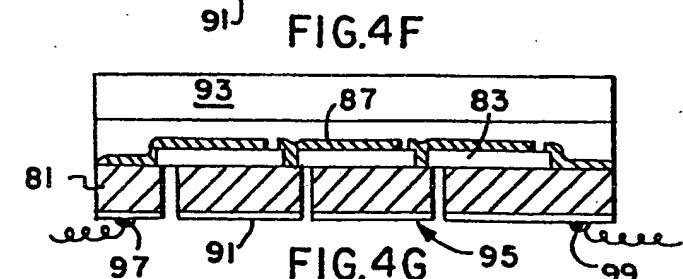
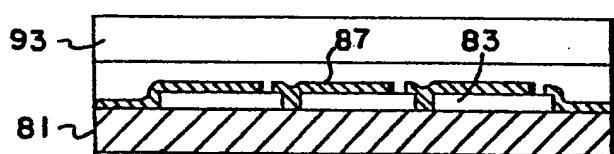
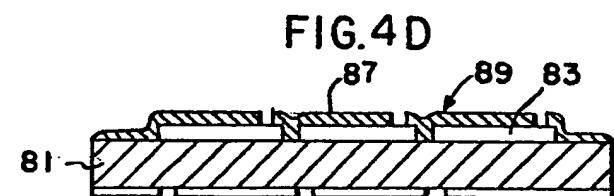
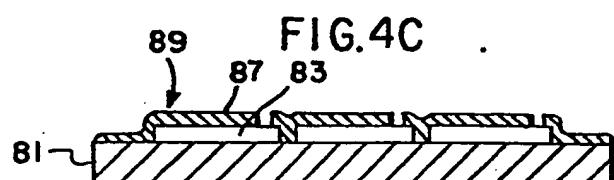
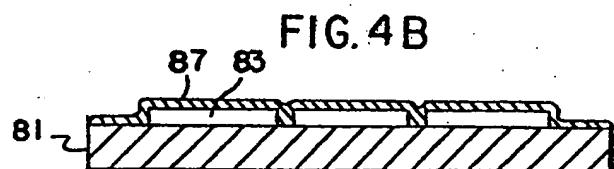
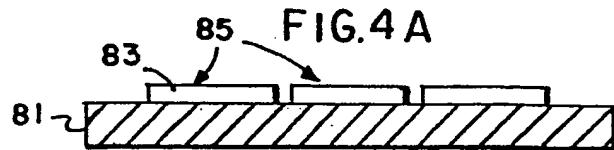
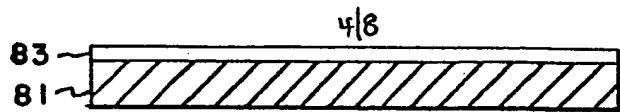
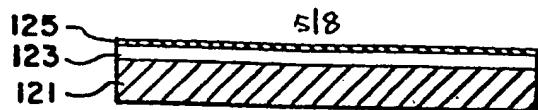


FIG. 3G

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FIG.5A

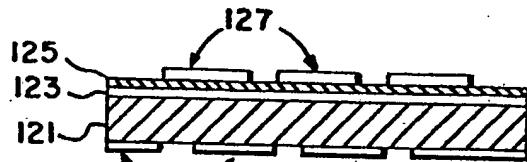


FIG.5B

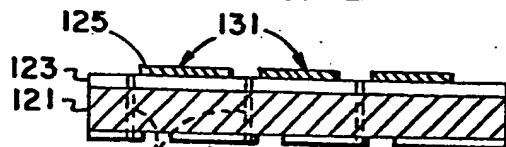


FIG.5C

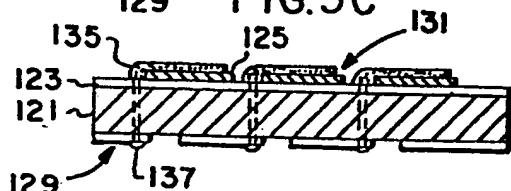


FIG.5D

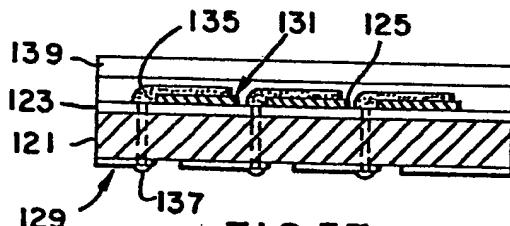


FIG.5E

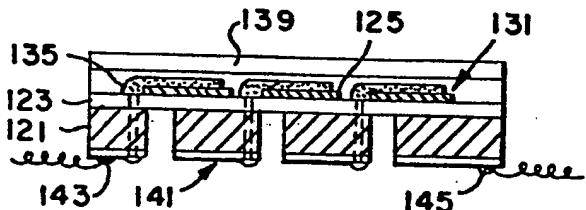


FIG.5F

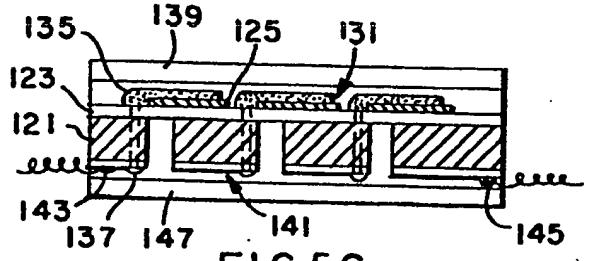


FIG.5G

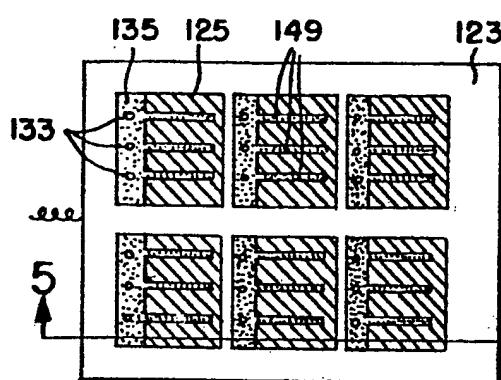


FIG. 6A

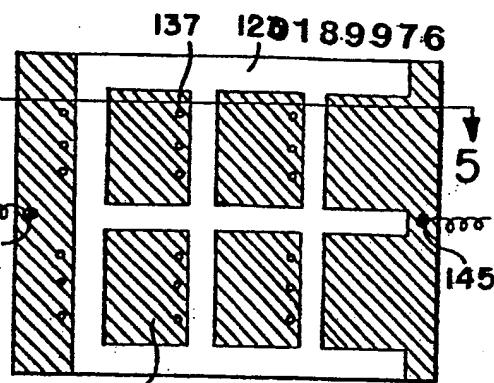


FIG. 6B

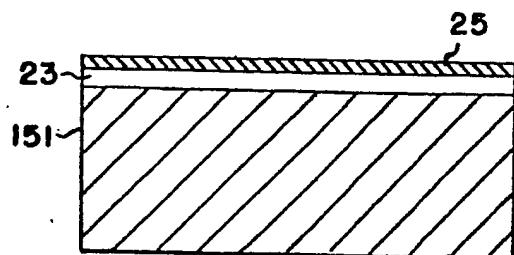


FIG. 7A

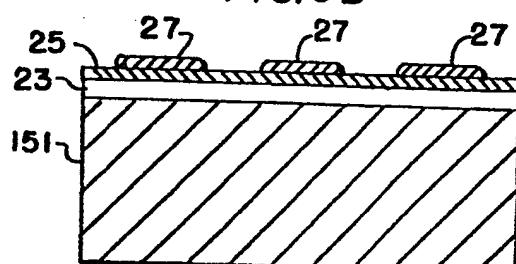


FIG. 7B

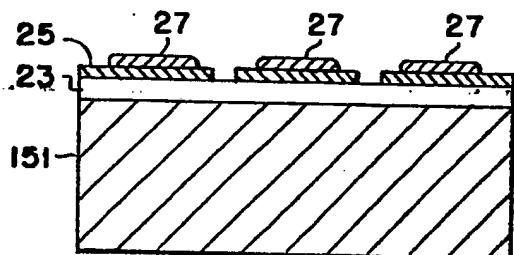


FIG. 7C

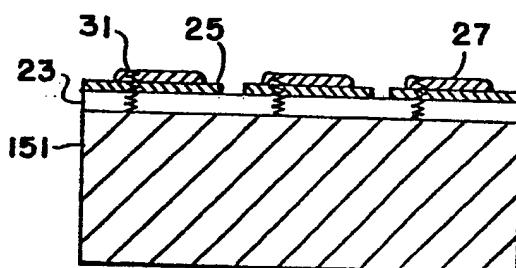


FIG. 7D

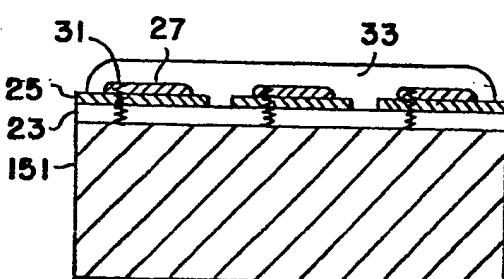


FIG. 7E

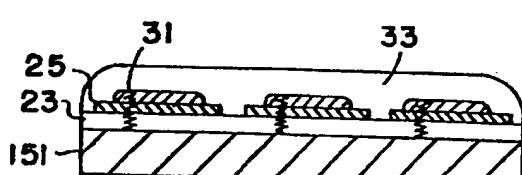


FIG. 7F

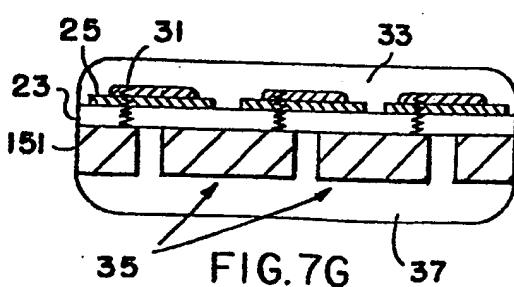
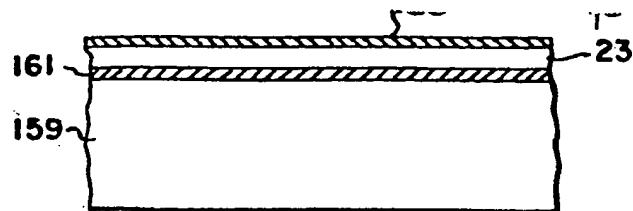


FIG. 7G



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FIG. 8A

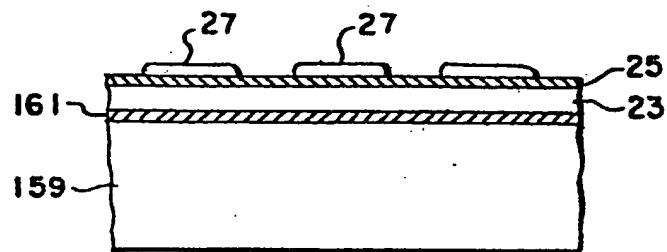


FIG. 8B

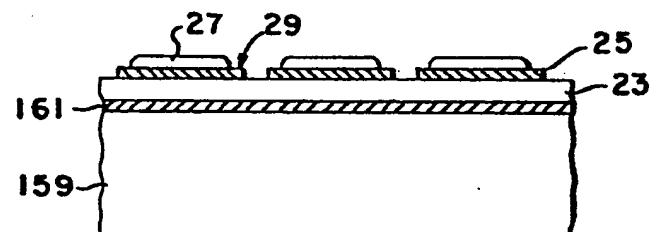


FIG. 8C

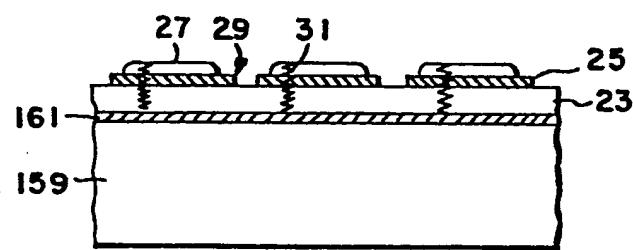


FIG. 8D

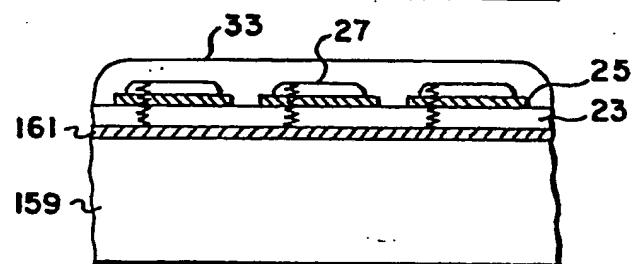


FIG. 8E

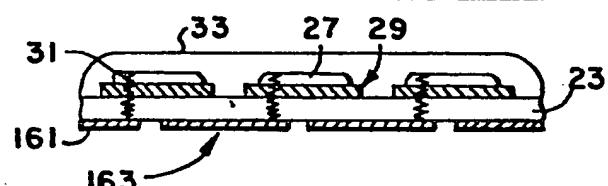


FIG. 8F

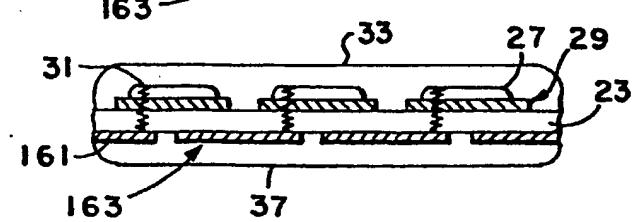


FIG. 8G

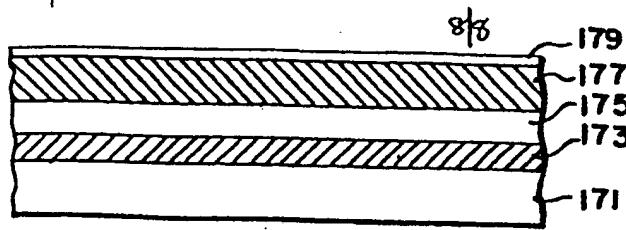


FIG. 9A

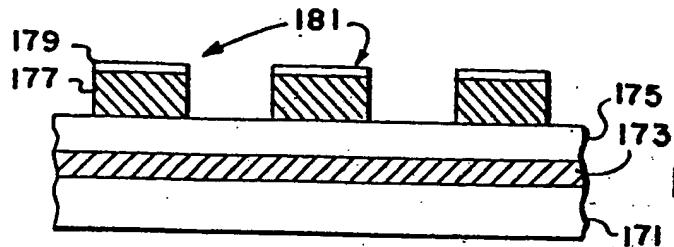


FIG. 9B

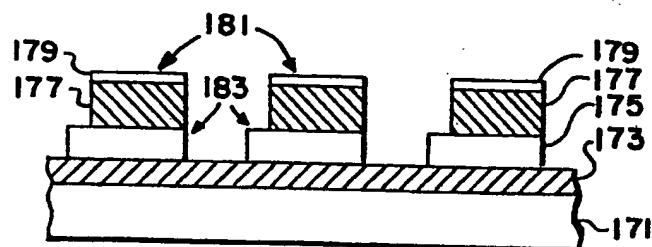


FIG. 9C

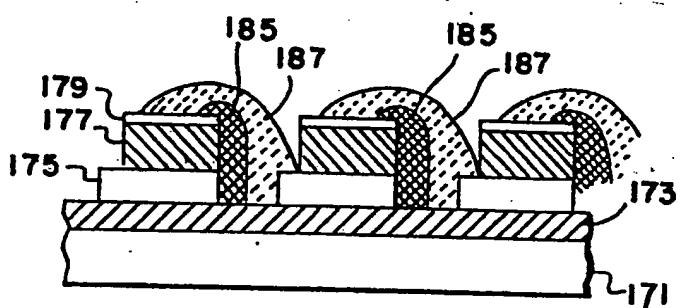


FIG. 9D

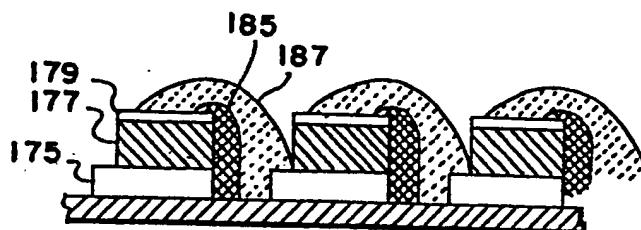


FIG. 9E